Vol 14 No 9, September 2005
1009-1963/2005/14(09)/1839-05

Chinese Physics

© 2005 Chin. Phys. Soc.
and IOP Publishing Ltd

Bound soliton pulses in a passively mode-locked fibre ring laser*

Zhang Shu-Min(张书敏)[a)b)], Lü Fu-Yun(吕福云)[b)†], Gong Yan-Dong(龚延洞)[a)], Zhou Xiao-Qun(周小群)[a)], Yang Xiu-Feng(杨秀峰)[a)], and Lü Chao(吕 超)[a)]

[a)] *Lightwave Department, Institute for Infocomm Research (I2R), Singapore* 637723, *Singapore*

[b)] *Institute of Physics, Nankai University, Tianjin* 300071, *China*

(Received 21 December 2004; revised manuscript received 28 April 2005)

The bound solitons in a passively mode-locked fibre ring laser are observed and their formation mechanism is summarized in this paper. In order to obtain stable bound solitons, a strong CW laser field at the centre of the soliton spectral is necessary to suppress and synchronize the random soliton phase variations.

Keywords: bound soliton, passively mode locking, fibre soliton laser
PACC: 4255

1. Introduction

Solitary wave generation is a generic property of many nonlinear dynamic systems. Optical solitons have attracted much attention because of their potential practical applications in optical communication and signal processing systems.[1−5] They have been observed in the passively mode-locked fibre lasers with different cavity configurations. Bound states of solitons, which are known as high-order soliton solutions of the nonlinear Schrodinger equation, have also been extensively studied. As is well known, solitons formed in the mode-locked systems have an oscillating tail. When there exists the interaction among slightly overlapped soliton pulses, the spatial local minima are their effective interaction potential. This will result in two or more fundamental solitons coexisting, and they have the same velocity and locate at the same position. This state of solitons is referred to as the bound-solitons.

In this paper, an experimental observation of several different bound solitons in the same fibre laser is reported. The stable harmonic mode-locking state of the bound-solitons is achieved by using an unstable CW component in the laser. Combining the optical spectrum graphs, oscilloscope and autocorrelation traces of the bound solitons, the detailed explanation about the formation mechanism of these states is given.

2. Experimental setup

The passively mode-locked fibre laser used in the experiment is schematically shown in Fig.1. An 8m-long erbium-doped fibre (EDF), whose Er^{3+} concentration is about 980ppm, with a group velocity dispersion of about −6ps/nm/km, is the gain medium of the laser. A 1480/1550 wavelength-division-multiplexing (WDM) is used to couple the pump light into the cavity. A pigtailed InGaAsP laser diode operating at 1480nm is used to pump the laser, and the maximum pump power output is 205.0mW. Unidirectional operation of the laser is enforced by a polarization-dependent-isolator (PI-ISO) in the cavity. Two polarization controllers (PCs) and a PI-ISO are mounded inside a 7-cm-long fibre bench to achieve accurate polarization adjustments. The output of the laser is taken via a 10% dispersion compensation fibre (DCF)

*Project supported by the Tianjin Key Project Foundation of China (Grant No 033183611), the National Natural Science Foundation of China (Grant No 60137010), and the National High Technology Research and Development Program of China (Grant No 2003AA312100).

†E-mail: lufy@nankai.edu.cn

coupler and the total length of the laser is 16m. An optical spectrum analyser (Ando AQ-6315B) is used to monitor the optical spectrum of the laser. An autocorrelator (APE PulseScope 50 Autocorrelator) and a 5-GHz sampling oscilloscope and a photodetector are used to study the evolution of the solitons.

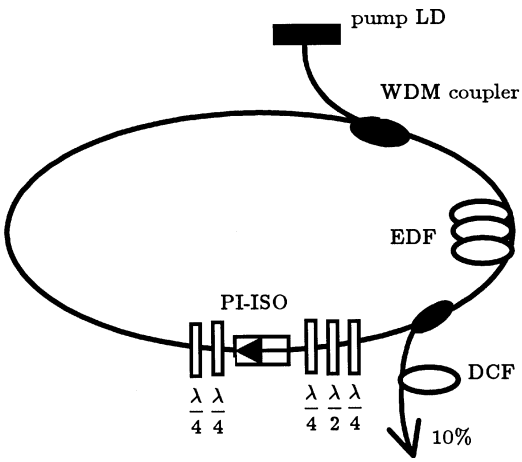


Fig.1. Schematic of the bound-solitons fibre laser.

3. Experimental results

In the experiment, the high-order soliton can be easily formed with a pump power of 189.2 mW. These high-order pulses are inherently unstable and eventually split into multiple fundamental solitons. Nevertheless, because of the unavoidable environmental perturbations and the interaction between solitons and the dispersion waves, the phases of the solitons vary randomly. This will cause a random interaction between the multiple fundamental solitons. The formed bound-solitons are based on the condition of the fixed phase difference among the solitons. In order to suppress the random soliton phase variations, an intracavity phase-locking technique is used to synchronize the random phase change of solitons.

In our experiment, by adjusting the PCs in the cavity, a very strong CW laser field at the centre of the soliton spectral is built up, then the phase of solitons can be locked and separation between solitons can be bounded.

However, under a high pump power, there exist many bound solitons in the cavity, which is the same as the normal soliton operation. And the bound solitons are unstable because they will compete for energy with the CW compound and the other bound solitons. When the pump power is reduced by adjusting the PCs carefully, the bound solitons will gradually rearrange themselves until a stable state is formed. In our experiment, a stable quasi-harmonic mode locking bound soliton, single bound soliton, the harmonic mode-locking mode and a train of bound solitons are obtained.

3.1. Quasi-harmonic mode locking of bound-solitons

Figure 2 shows the solitons spectrum, the autocorrelation and the oscilloscope traces of the quasi-harmonic mode locking with a pump power of 60mW. In Fig.2(a), the spectrum exhibits a strong modulation with a period of 5.84nm, which corresponds to a bound soliton spacing of 1.40ps in the time domain ($\Delta v = -\frac{c\Delta\lambda}{\lambda^2}$, where c is the speed of light in vacuum, see Fig.2(b)). The pulse duration is about 352fs if sech^2 pulse profile is assumed, which is measured from the main peak autocorrelation trace in Fig.2(b) (see the insert). Figure 2(c) shows the stably irregular distribution of eleven bound solitons in the cavity. Once the quasi-harmonic mode locking bound solitons have formed, they are very stable for hours even in the presence of a small perturbation such as small linear polarization or pump power variety.

In the experiment, the number of bound solitons will reduce one by one with carefully decreasing the pump power. After losing one pair of the bound-solitons, the rest will rearrange their relative positions in the cavity and be stabilized finally. This is because the bound solitons can interact among themselves through the dispersion waves and result in various states of multiple bound-solitons. Figures 2(d) and 2(e) show the cases with the pump powers of 50mW and 46mW, respectively. When the pump power is reduced to 40mW, there will exist only one stable bound solitons in the cavity. If we further reduce the pump power, the bound solitons will disappear suddenly and be replaced by the CW state. It is noticed that with the decrease of the bound solitons, there is no difference in observation between the optical spectrum and the autocorrelation trace except the strength is decreasing.

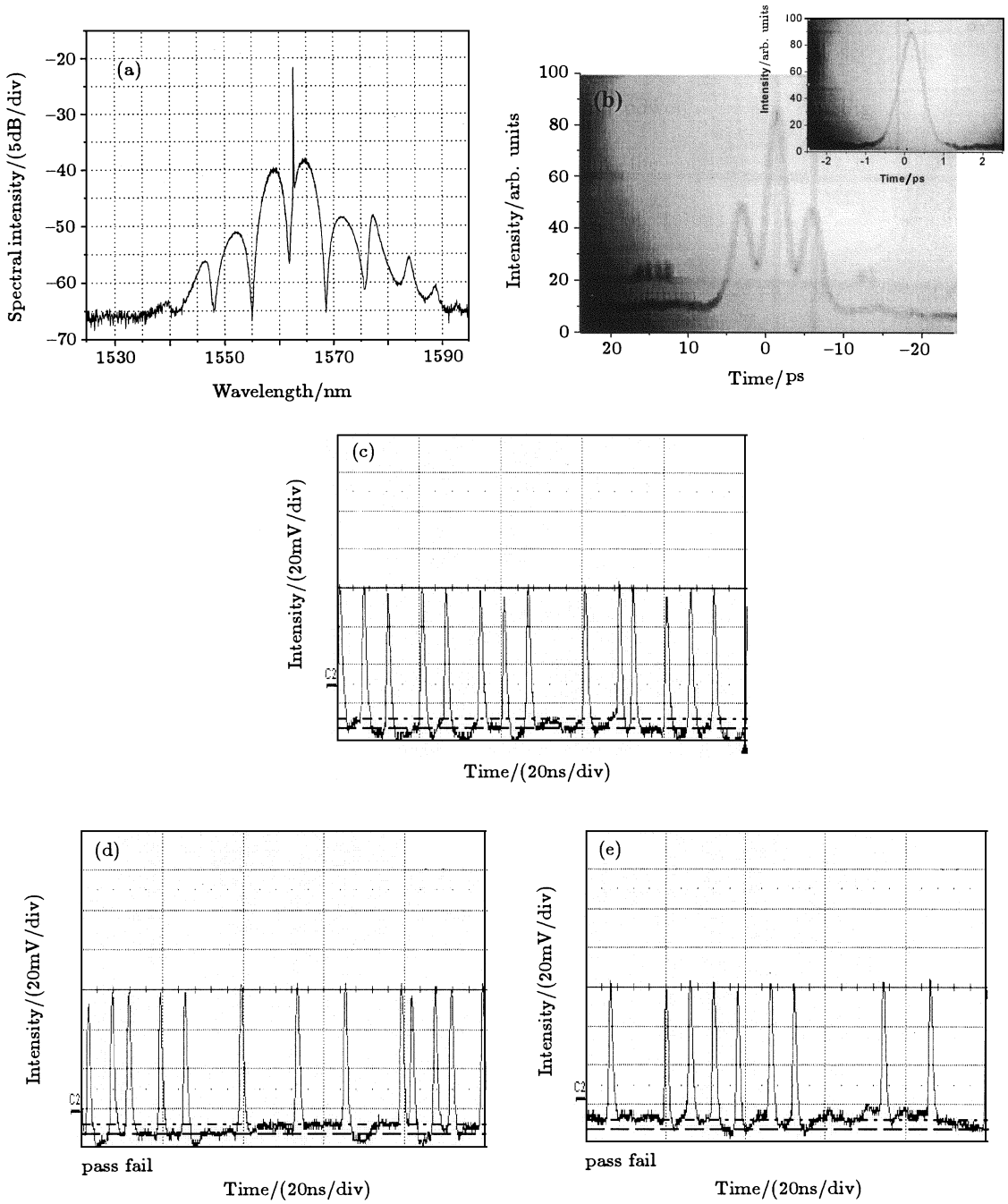


Fig.2. (a) The spectrum of the quasi-harmonic mode-locking of bound-soliton, (b) Autocorrelation trace of the quasi-harmonic mode-locking of bound-solitons, (c) Oscilloscope trance of quasi-harmonic mode-locking of bound-soliton at pump power of 60mW, (d-e) Oscilloscope trances of quasi-harmonic mode-locking of bound-soliton at different pump powers, Figure 2(d) is for 50mW, and Figure 2(e) is for 46mW.

3.2. Harmonic mode–locking of bound-soliton

By adjusting the pump power and the position of PCs until the CW compound becomes unstable, the stable harmonic mode locking of bound-solitons can be easy formed. Figure 3 shows the oscilloscope trace of a typical 5 harmonic mode locking bound-solitons. Based on the experimental results, it is believed that, apart from the gain recovery and the acoustic effect,[6,7] the unstable CW lasing should be another mechanism to form the passive harmonic bound-solitons mode locking. This can be understood as follows: the unstable CW fills in the whole laser cavity controlled by the resonance condition, which results in the interaction between the unstable CW and every bound solitons. That is to say, the interaction of all bound solitons will work up, when all bound-solitons in the cavity are in an equal period,

the distribution of steady state bound-solitons can be built up. We refer to this steady state as the harmonically mode-locked state. The pulse repetition rate can also be changed easily by decreasing or increasing the pump power.

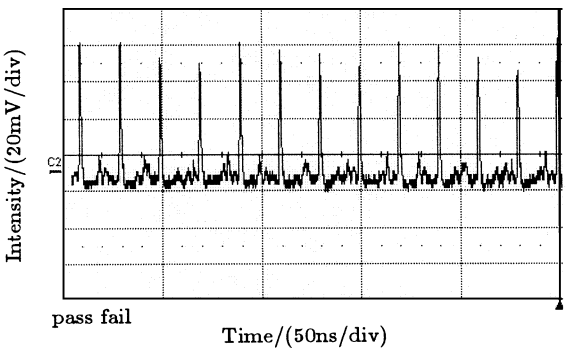


Fig.3. Oscilloscope trance of harmonic mode-locking of bound-soliton, the cavity round-trip time is about 80ns.

3.3. The trains of bound solitons

In the experiment, another stable operation, the trains of bound solitons, is also observed by adjusting the PCs in the cavity. Figures 4(a) and 4(b) give the spectrum and the autocorrelation trace of this mode, respectively, with a pump power of 64mW. Comparing Figs.4(a) with Fig.2(a), we can see that the spectrum of the bound solitons trains overlaps a very small modulation on the strong modulations. The period of the small modulation is about 0.59nm, which corresponds to the separation of 13.86 ps between two bound solitons. The strong modulation period of 5.84nm is a direct consequence of a very close soliton spacing of 1.40ps in the time domain. Figure 4(b) shows that, with the scan range of 50ps, there are three bound solitons, and each of them is a bound state of twins (see the insert). In particular, all of the bound states have exactly the same soliton spacing and phase relationship. It is noticed that our photodetector is of 5GHz, which is much slower than the bound solitons repetition period of 1.4ps. Hence, we can not discern the clear and stable bound soliton traces on the oscilloscope.

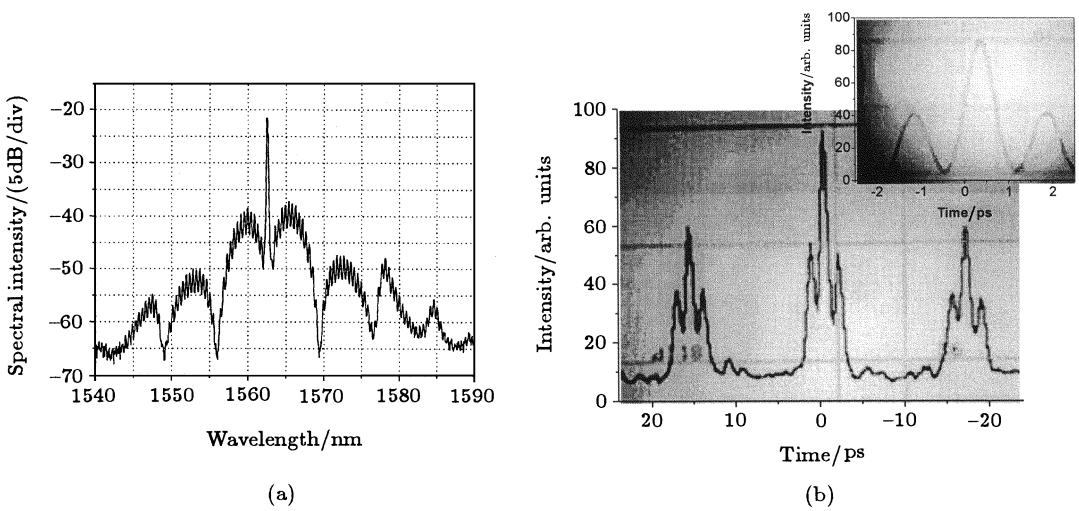


Fig.4. (a) Spectrum of the trains of bound solitons, (b) Autocorrelation trace of the trains of bound solitons.

It should be noticed, in the stable state of the bound-solitons, that the oscilloscope trace is similar to that of the signal soliton.[3] So the bound-solitons need to be verified by autocorrelation trace and the optical spectrum at the same time.

4. Conclusions

An experimental observation of several different bound solitons in one fibre laser has been reported, including its four different stable operation states: quasi-harmonic mode-locking, single bound solitons, the harmonic mode-locking mode and a train of bound solitons. A detailed explanation about the formation mechanism has been given. Our results show that a strong CW component is required to obtain the bound state of solitons. In the formation of the harmonic mode-locking state, an unstable CW spectral component in the laser cavity also plays an important role, apart from the gain recovery and acoustically induced soliton interactions. And the generation and formation of the bound-soliton must be verified synchronously by autocorrelation trace and the optical spectrum at the same time in the experiment.

References

[1] Zhang J Y, Song L J and Li S C 2001 *Acta Opt. Sin.* **21** 1482 (in Chinese)

[2] Liu D F, Chen G F and Bai J T 2000 *Acta Phys. Sin.* **49** 241

[3] Grudinin A B and Gray S 1997*J. Opt. Soc.* B **14** 146

[4] Smith K, Greer E J and Wytt R 1991 *Electron. Lett.* **27** 244

[5] Afanasjev V V, Malomed B A and Chu P L 1997 *Phys. Rev.* E **56** 6020

[6] Pilipetskii A N, Golovchenko E A and Menyuk C R 1995 *Opt. Lett.* **20** 907

[7] Kutz J N, Collings B C, Bergman K *et al* 1998 *IEEE J. Quantum Electron.* **34** 1749